# The WFIRST Microlensing Survey: An Overview.

**Community Astrophysics with WFIRST.**
**March 2, 2016**

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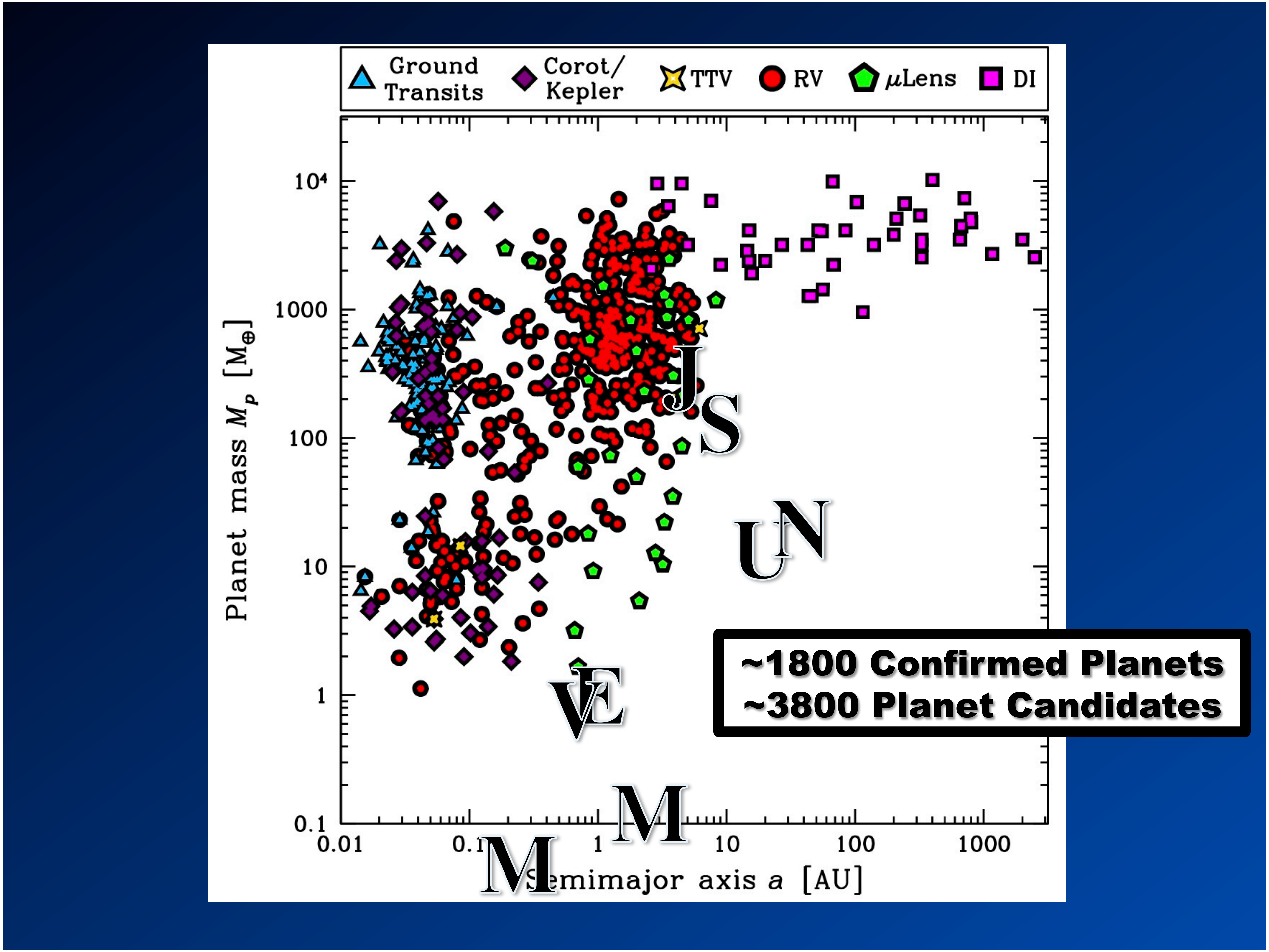
(on behalf of the WFIRST μSIT)
(All yields and simulations by Matthew Penny)

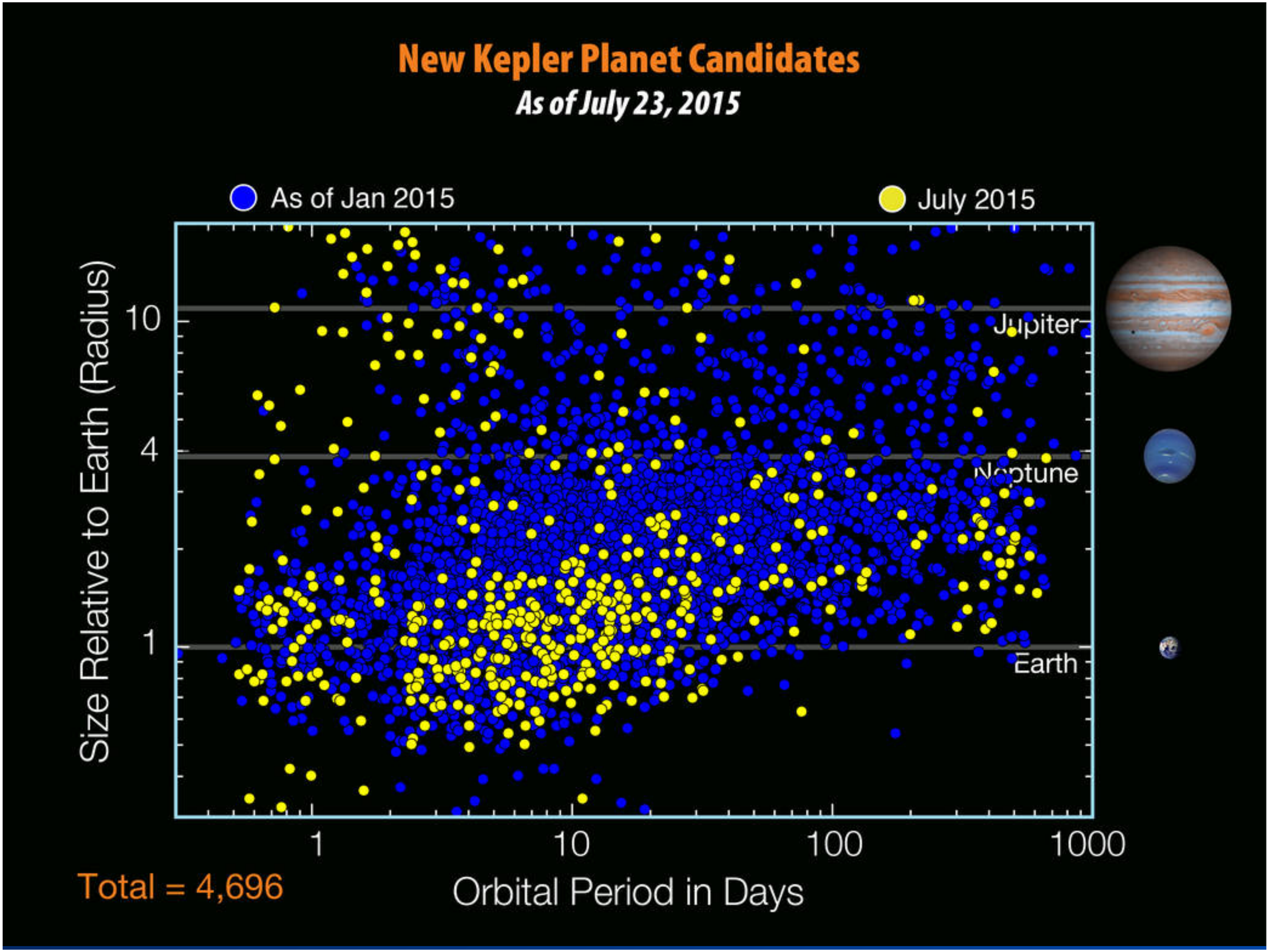
# Primary Science Goal.

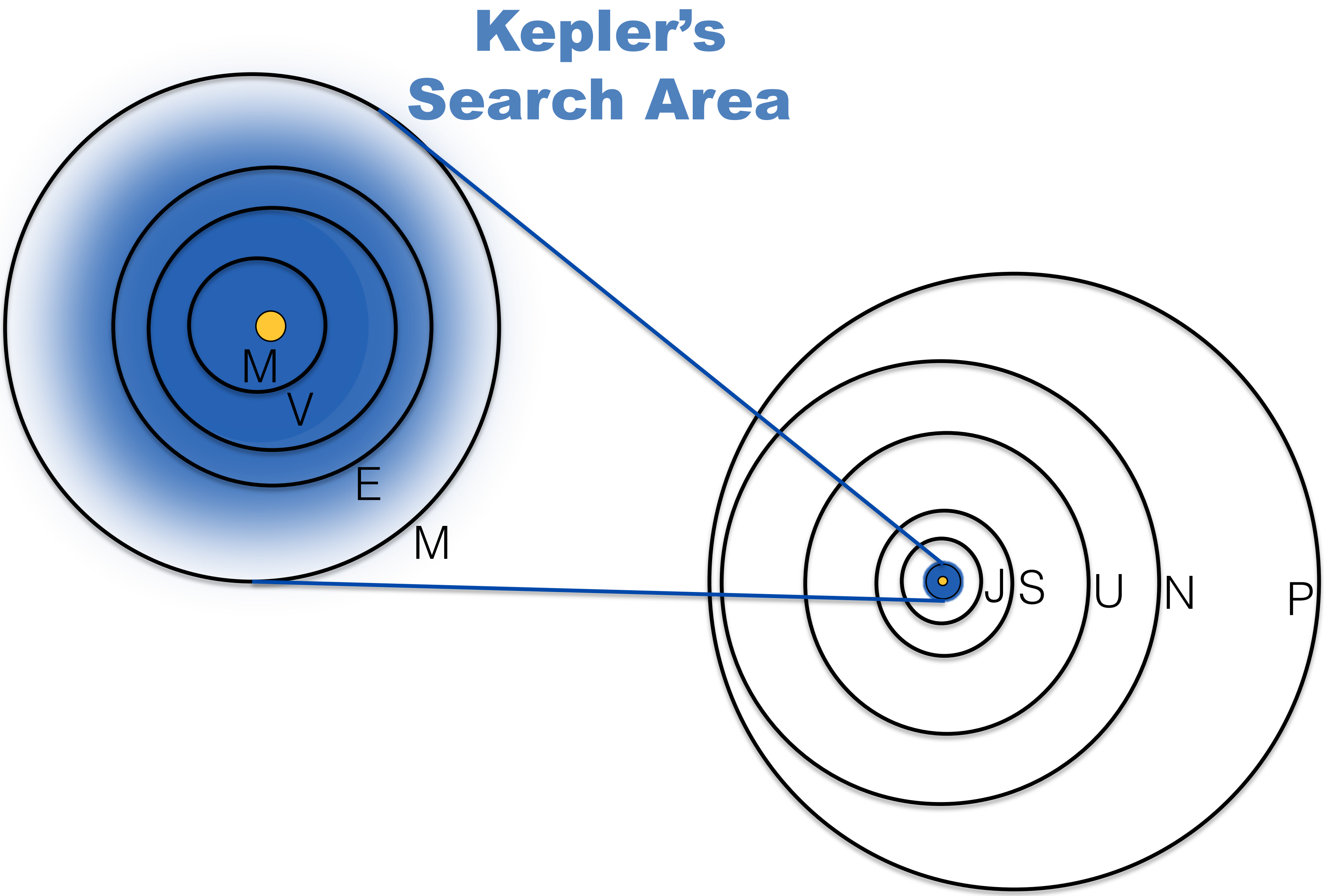
*"Complete the statistical census of planetary systems in the Galaxy, from the outer habitable zone to free floating planets, including analogs of all of the planets in our Solar System with the mass of Mars or greater."*

# Why Do We Need to Complete the Exoplanet Census?



Ground Transits
Corot/ Kepler
TTV
RV
μLens
DI
Planet mass $M_p$ [$M_\oplus$]
Semimajor axis $a$ [AU]
$10^4$
1000
100
10
1
0.1
0.01
0.1
1
10
100
1000
J
S
U
N
V
E
M
M
~1800 Confirmed Planets
~3800 Planet Candidates

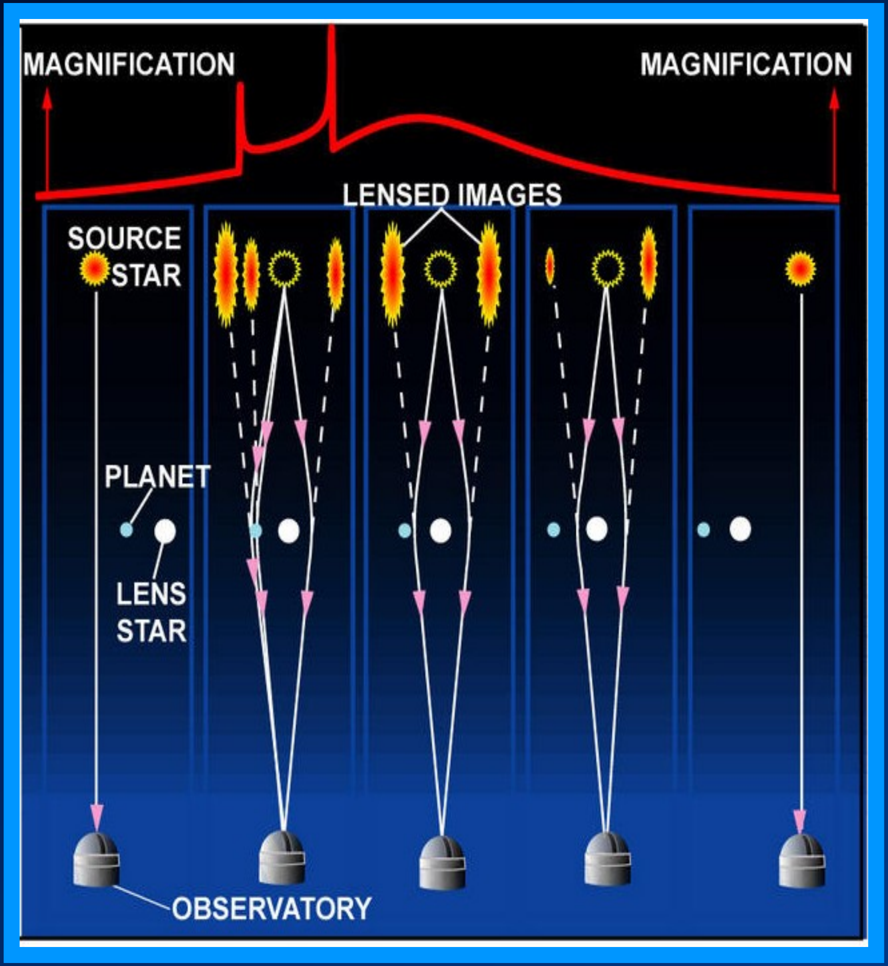

New Kepler Planet Candidates
As of July 23, 2015
As of Jan 2015
July 2015
Size Relative to Earth (Radius)
10
4
1
Jupiter
Neptune
Earth
1
10
100
1000
Orbital Period in Days
Total = 4,696

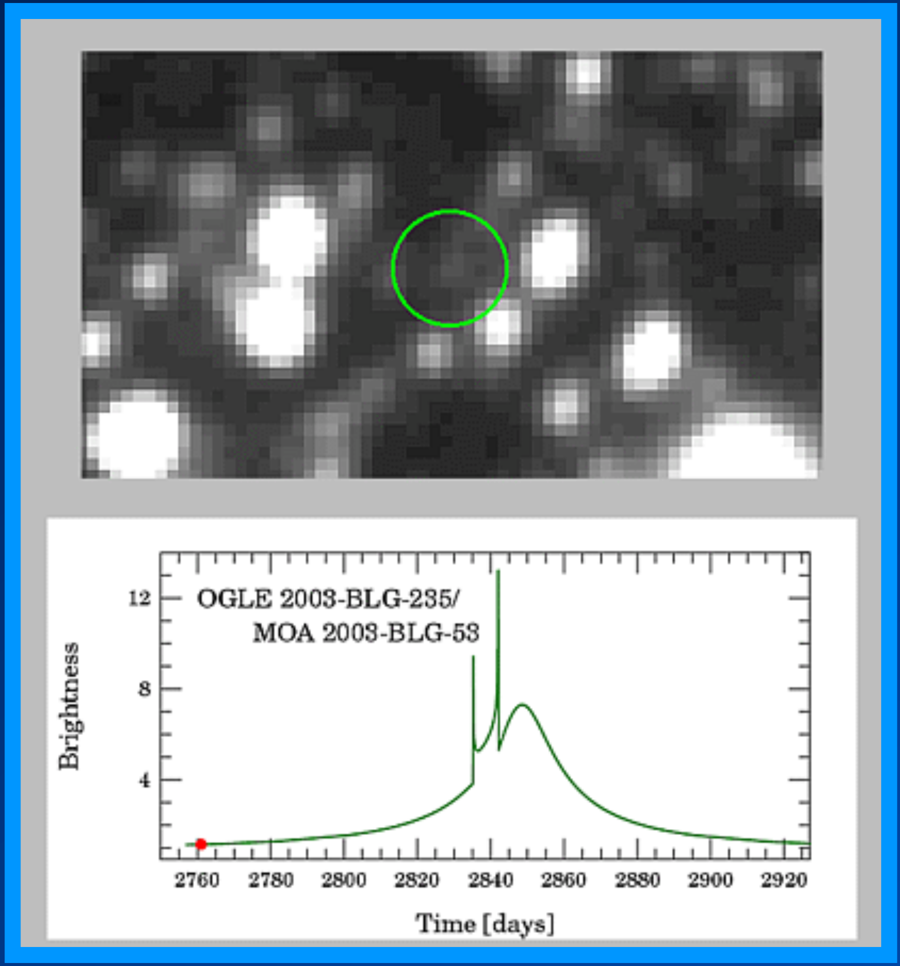

Kepler's
Search Area
M
V
E
M
J
S
U
N
P

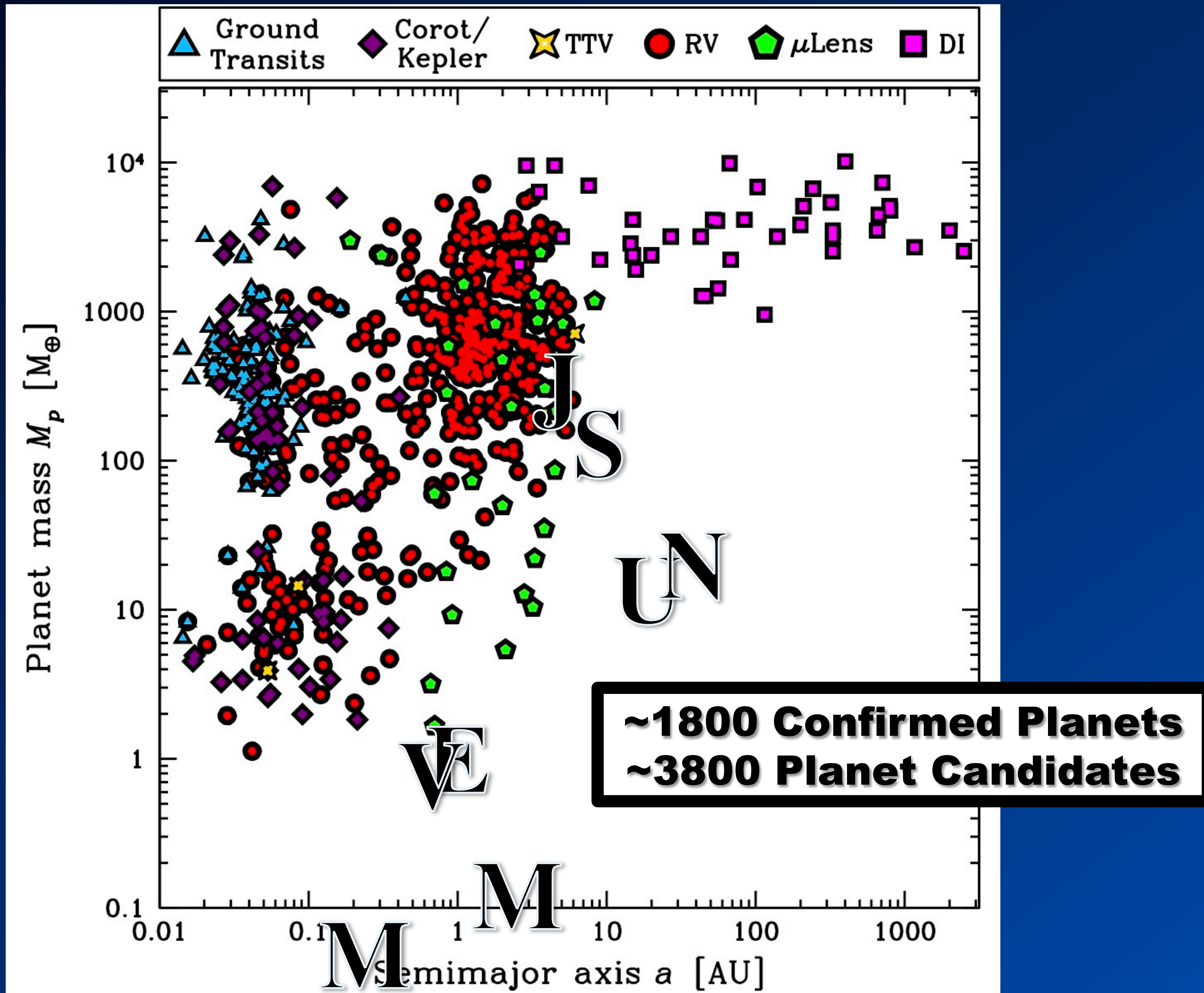
# Why complete the census?

- A complete census is likely needed to understand planet formation and evolution.
  - Most giant planets likely formed beyond the snow line.
  - Place our solar system in context.
  - Water for habitable planets likely delivered from beyond the snow line.
- Mother nature is more imaginative that we are.

# Microlensing.





Ground Transits
Corot/ Kepler
TTV
RV
μLens
DI
Planet mass $M_p$ [$M_\oplus$]
Semimajor axis $a$ [AU]
0.1
1
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$10^4$
0.01
0.1
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J
S
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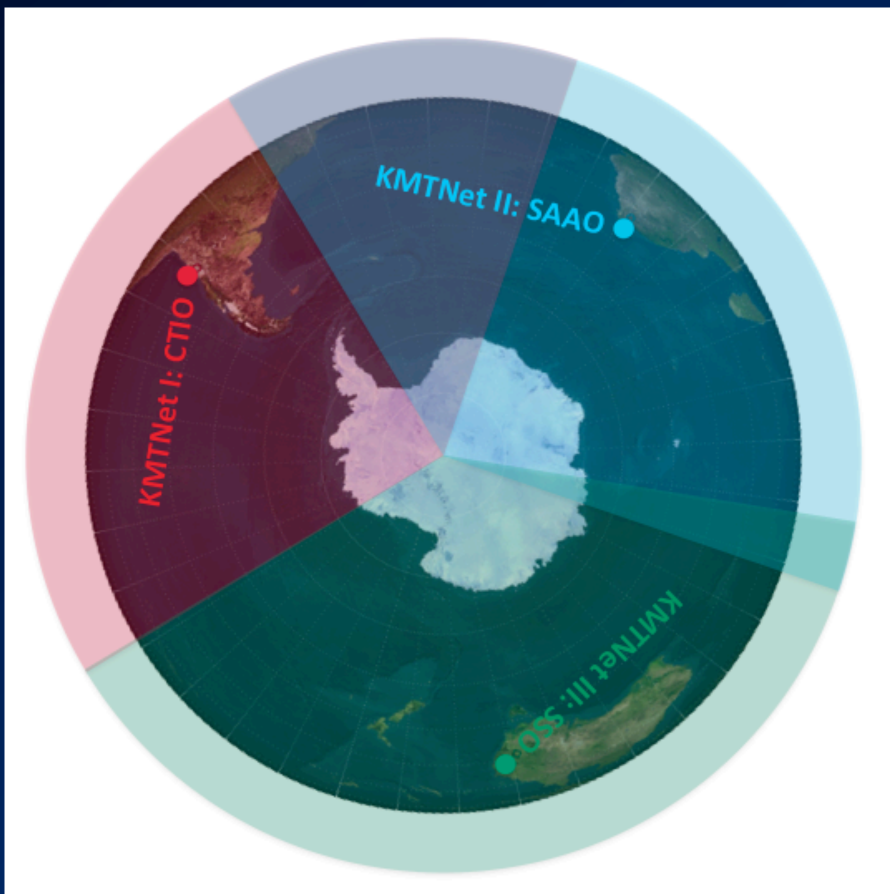
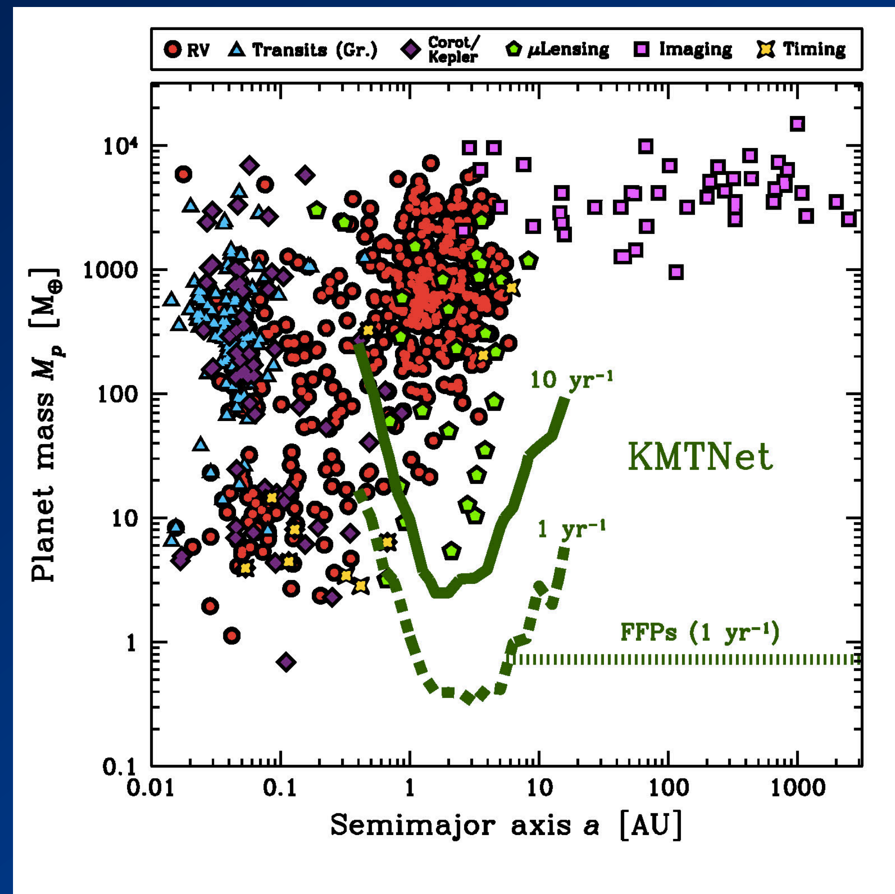
M
M
~1800 Confirmed Planets
~3800 Planet Candidates

# Korean Microlensing Telescope Network.

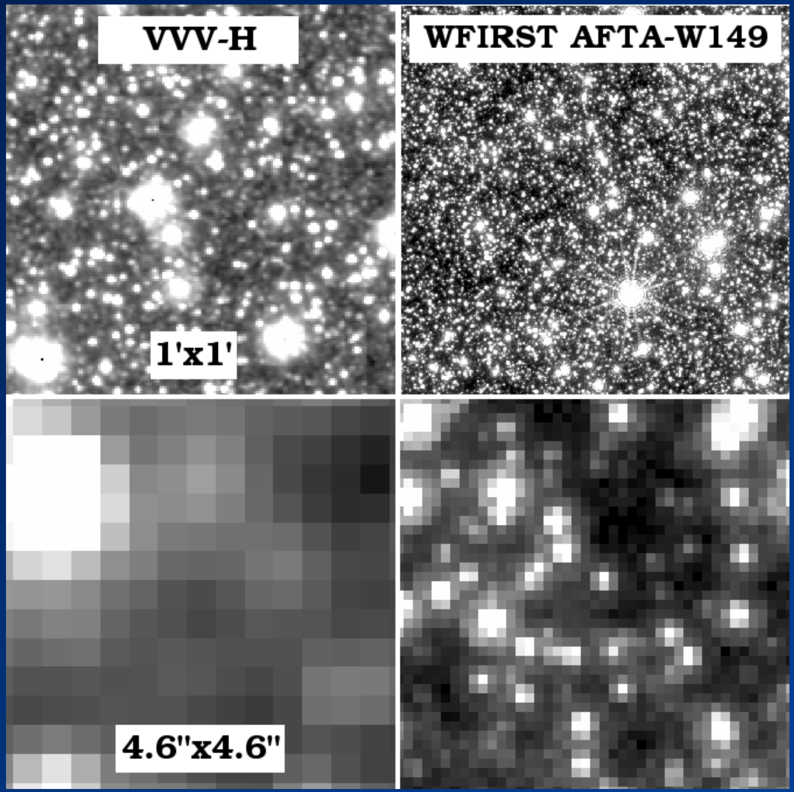



(Henderson et al. 2014)

# Ground vs. Space.

- Infrared.
  - More extincted fields.
  - Smaller sources.
- Resolution.
  - Low-magnification events.
  - Isolate light from the lens star.
- Visibility.
  - Complete coverage.
- Smaller systematics.
  - Better characterization.
  - Robust quantification of sensitivities.




Science enabled from space: sub-Earth mass planets, habitable zone planets, free-floating Earth-mass planets, mass measurements.

(Bennett & Rhie 2002)

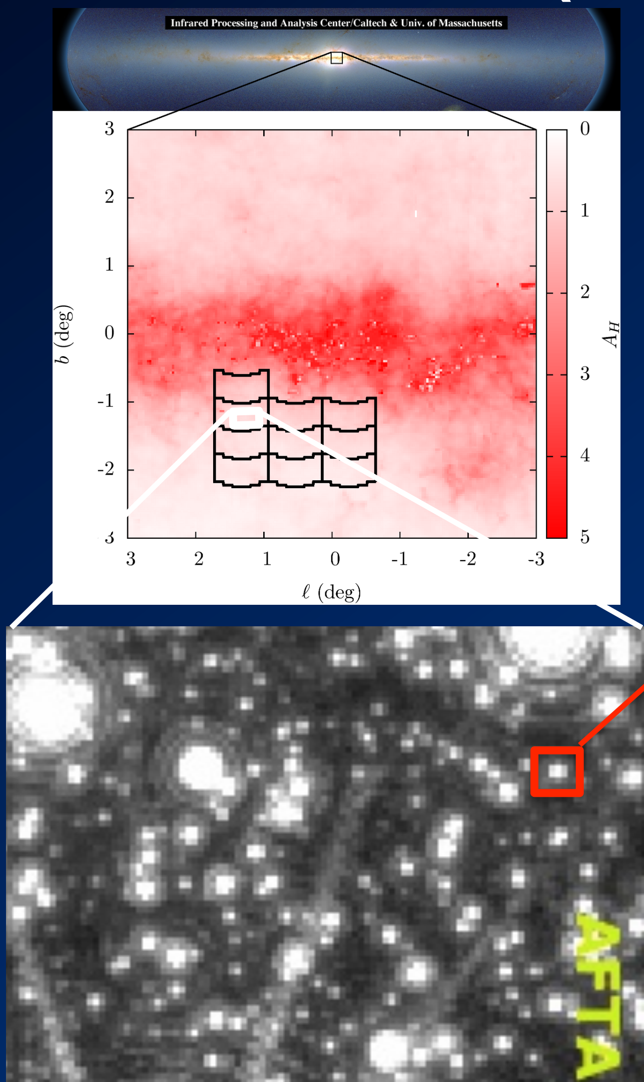
# WFIRST.

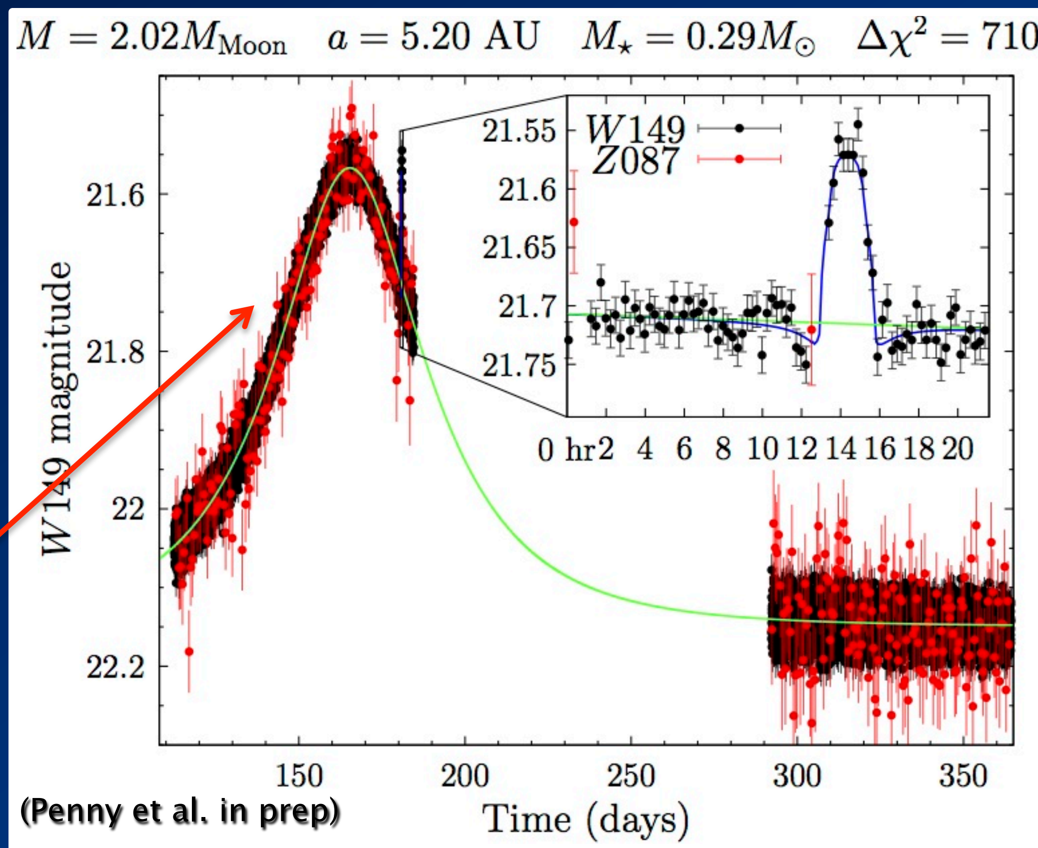
# Microlensing Survey.

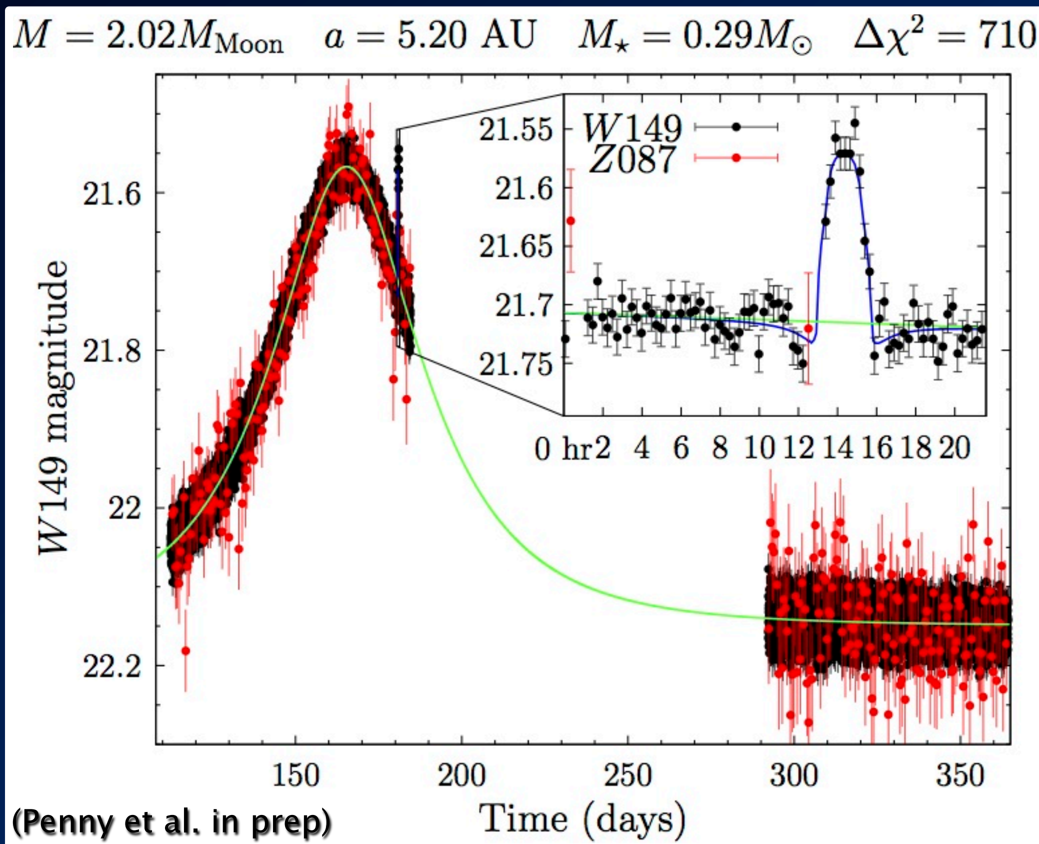
Properties.

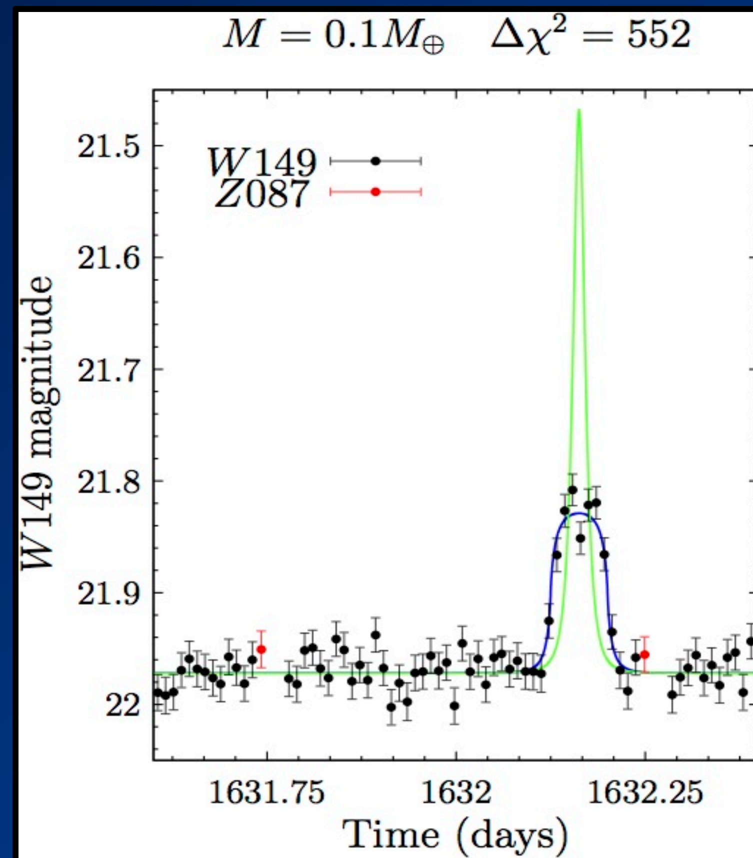
- ~3 sq. deg (10 fields).
- ~432 days (6 seasons of 72 days each).
- ~15 minute cadence, 52s in W149.
- ~12 hour cadence, 290s for Z087.
- ~85% of the area will have ~40,000 measurements per star ($N^{-1/2} = 1/200$).
- ~60 million stars down to $H_{AB}<21.6$.
- 2 million seconds of integration time.
- ~2.5 billion photons detected for a $H_{AB}=19.6$ star

# Microlensing Simulations.
## (Matthew Penny)



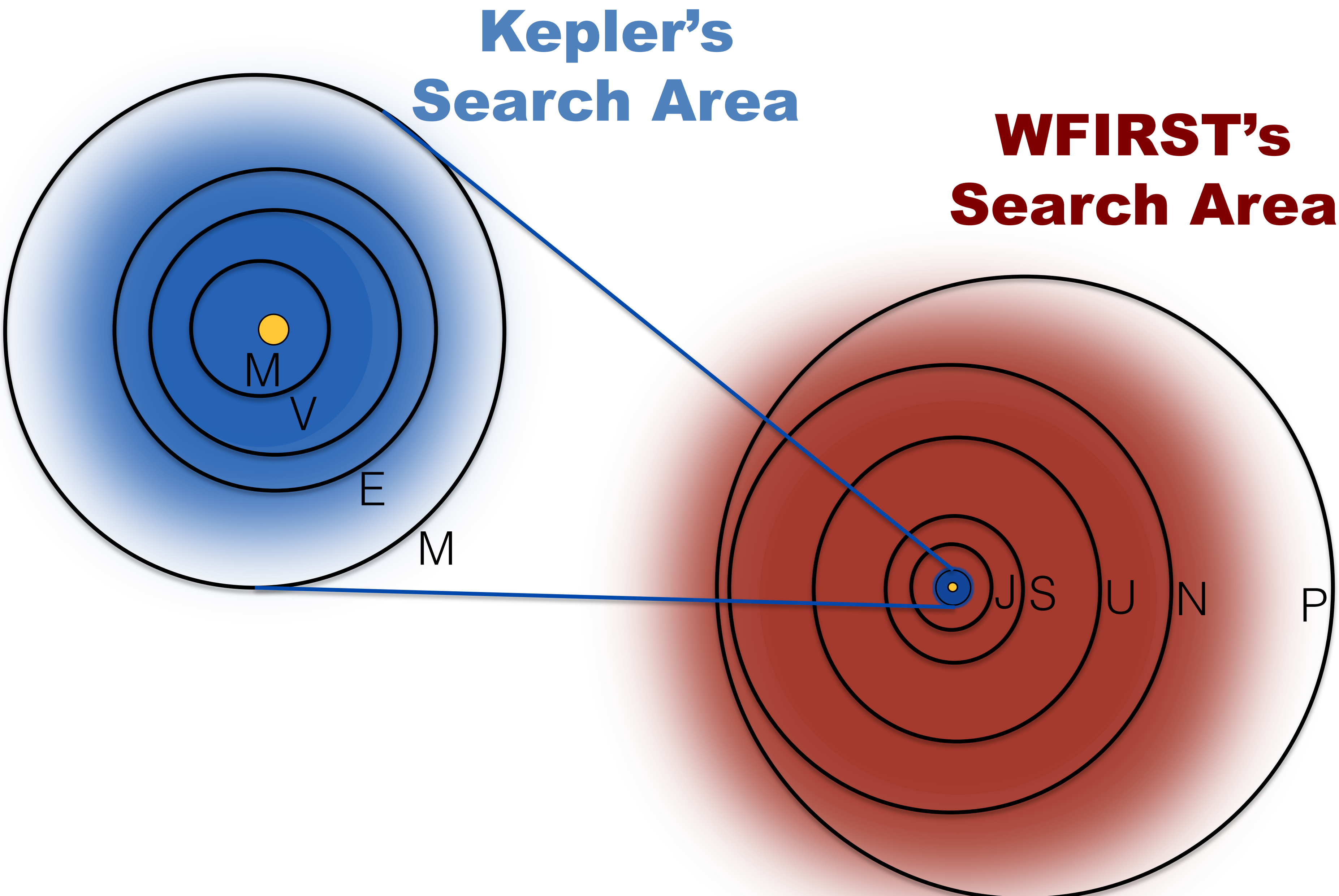






**2 × Mass of the Moon @ 5.2 AU (~27 sigma)**

**Free floating Mars (~23 sigma)**



Kepler's
Search Area
WFIRST's
Search Area
M
V
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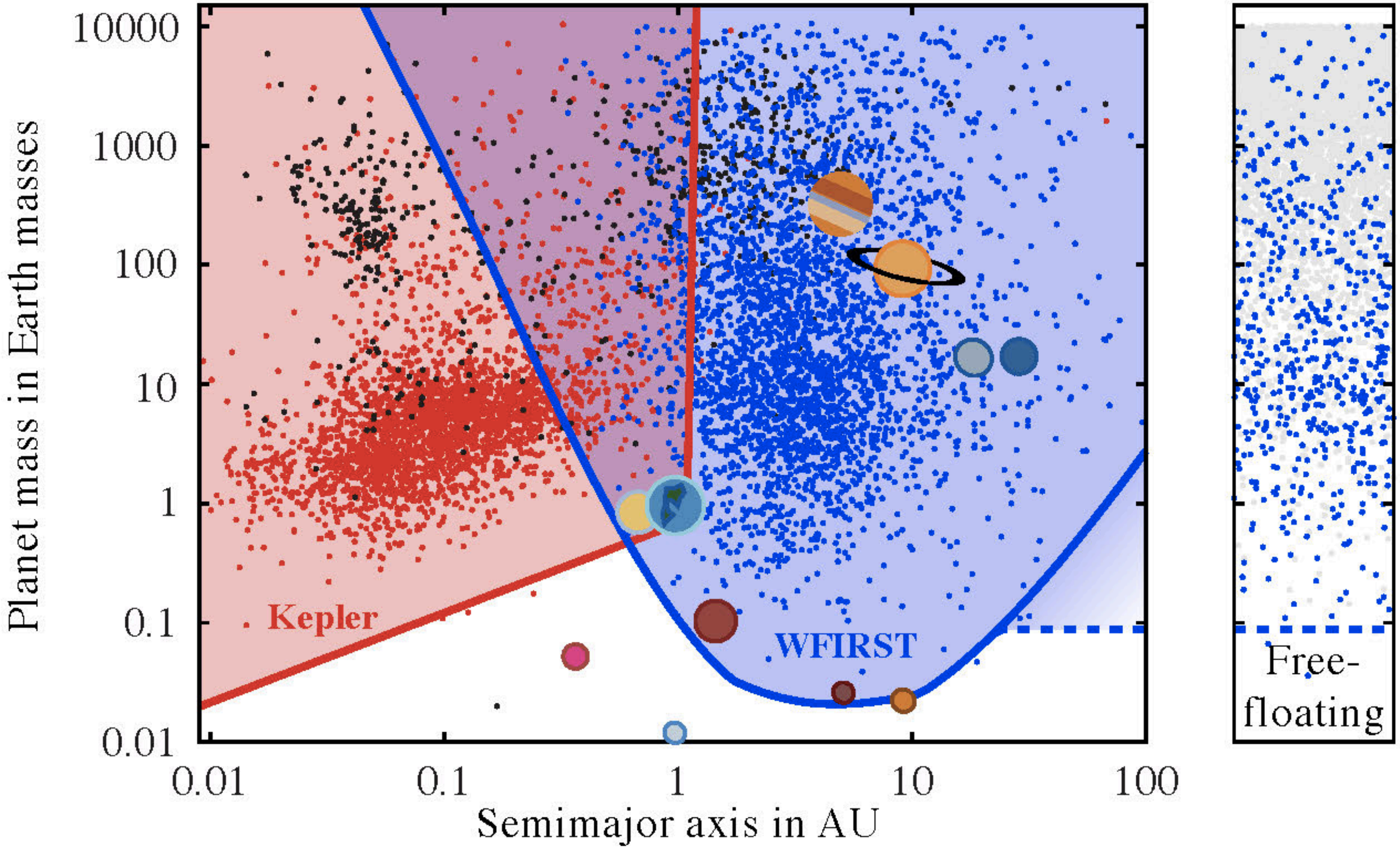



(Penny et al. in prep)

# Predicted Planet Yields.

Bound

| $M/M_{\oplus}$ | WFIRST-IDRM (432 days) | WFIRST-DRM1 (432 days) | WFIRST-DRM2 (266 days) | WFIRST-AFTA (357 days) | WFIRST-AFTA (417 days) |
|---|---|---|---|---|---|
| 0.1 | 22 | 30 | 18 | 50 | 58 |
| 1 | 208 | 233 | 173 | 367 | 429 |
| 10 | 575 | 793 | 551 | 1030 | 1203 |
| 100 | 470 | 629 | 439 | 726 | 849 |
| 1000 | 298 | 367 | 261 | 426 | 497 |
| Total | 1701 | 2052 | 1442 | 2599 | 3036 |

All yields by Matthew Penny.

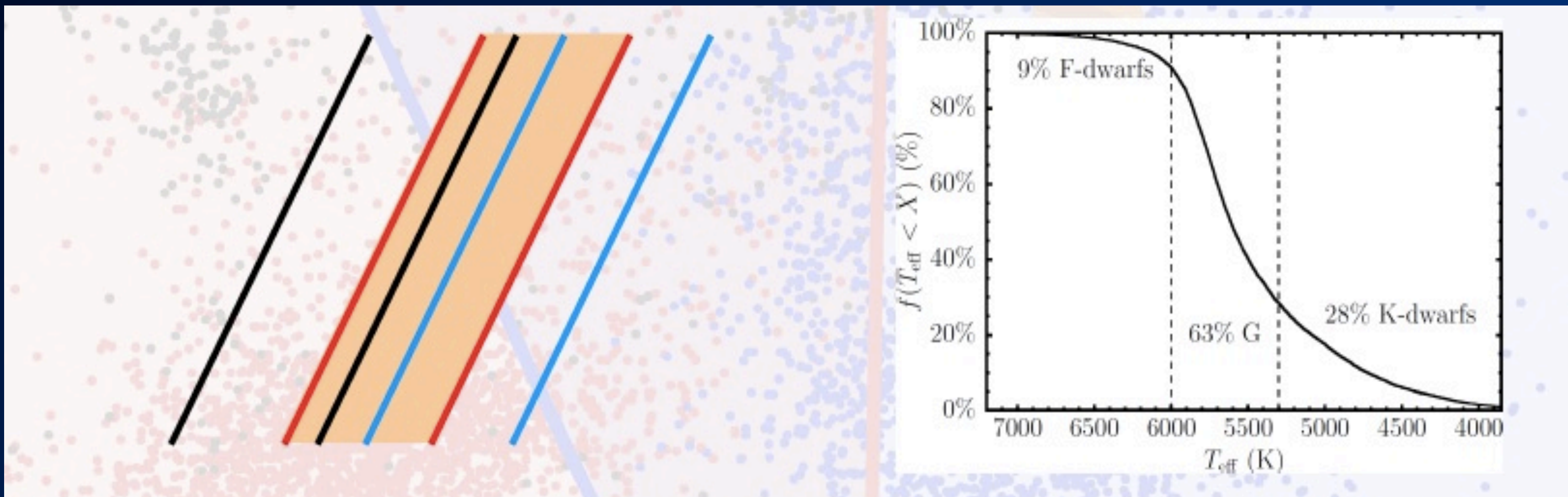
# Predicted Planet Yields.

Free Floating

| $M/M_\oplus$ | One per star | Cassan et al. |
|---|---|---|
| 0.001 | 0.002 | 0.004 |
| 0.01 | 0.54 | 1.1 |
| 0.1 | 5.7 | 11 |
| 1 | 28 | 57 |
| 10 | 108 | 134 |
| 100 | 356 | 82 |
| 1000 | 1161 | 50 |
| Total | 1659 | 364 |

All yields by Matthew Penny.

# Habitable Planets.

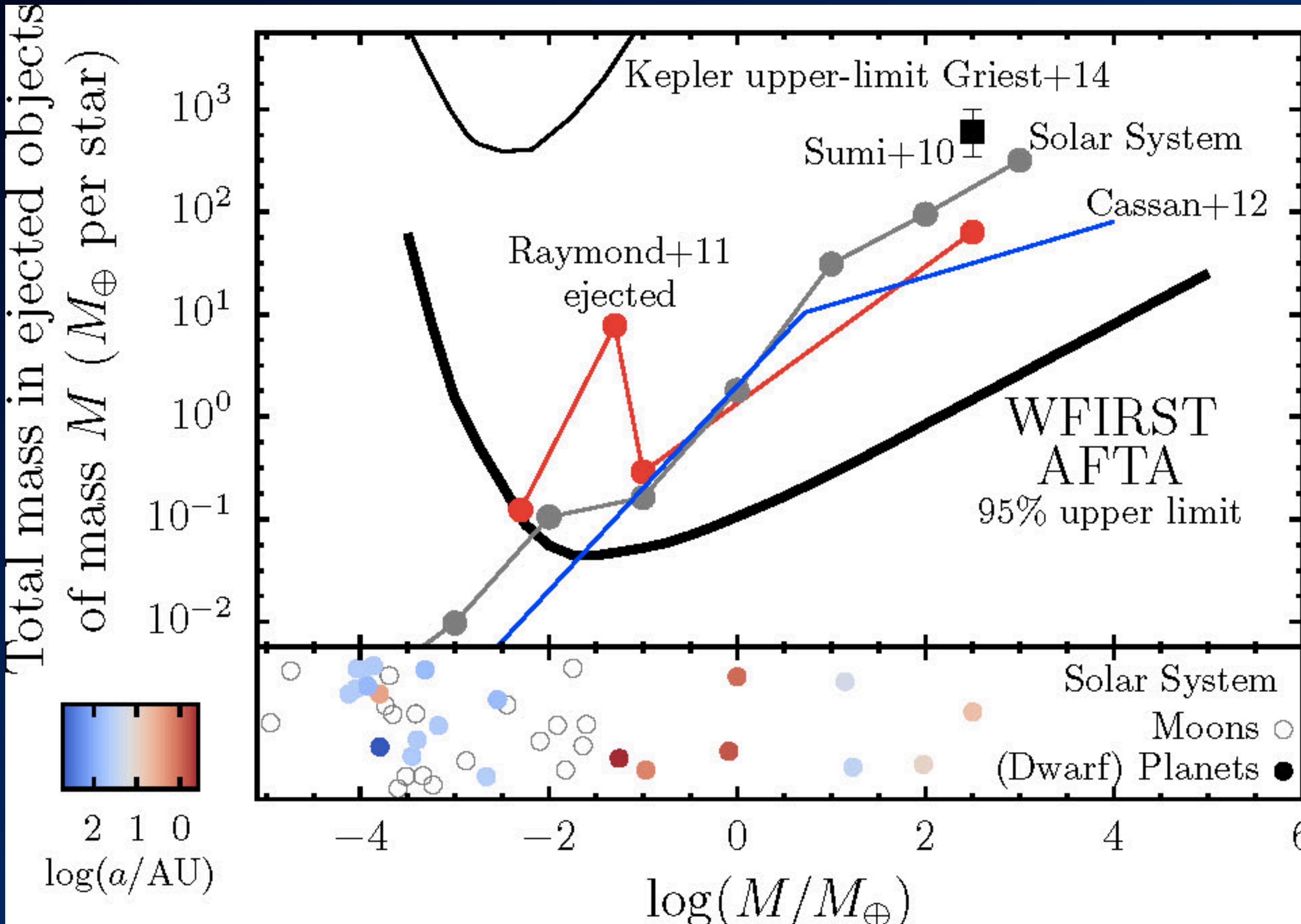



| AFTA-WFIRST yields if 1 planet per star in shifted HZ around FGK dwarfs | | | |
|---|---|---|---|
| **Mass/HZ** | **HZ x 1.0**<br>**0.99–1.68 AU** | **HZ x 1.5**<br>**1.49–2.52 AU** | **HZ x 2.0**<br>**1.98–3.36 AU** |
| 10.0 Mearth | 8.2 | 25.0 | 52.9 |
| 3.2 Mearth | 3.2 | 11.1 | 23.9 |
| 1.0 Mearth | 1.1 | 4.5 | 9.9 |

1.0 dex

0.3 dex

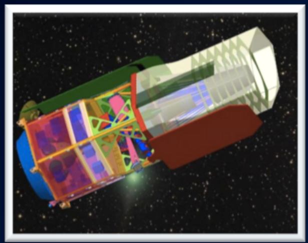
**(Penny et al., in prep.)**



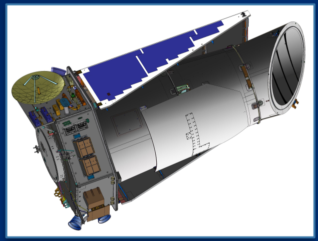

(Penny et al., in prep)

WFIRST-AFTA will measure the compact object mass function over at least 8 orders of magnitude in mass (from Mars to ~30 solar masses).

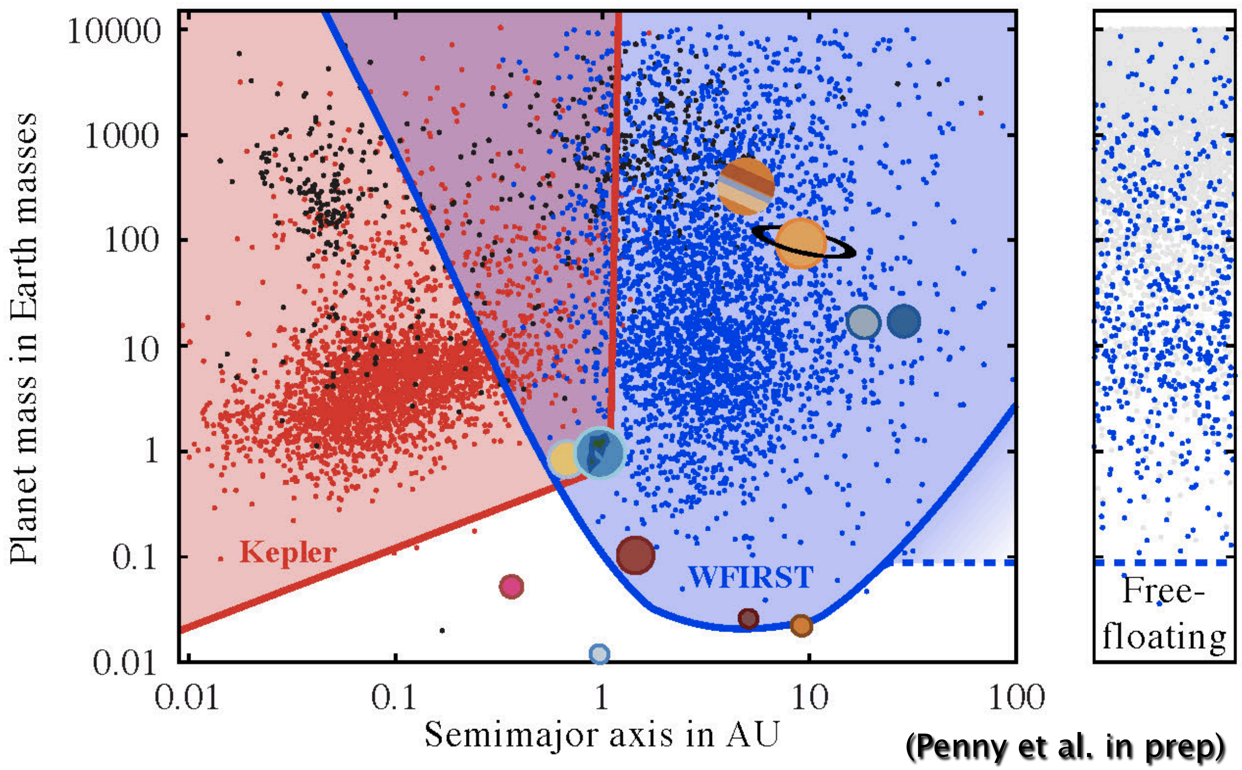
# Completing the Exoplanet Census.



Together, Kepler and WFIRST complete the statistical census of planetary systems in the Galaxy.



- ~2600 detections.
- Some sensitivity to "outer" habitable zone planets.
- Sensitive to analogs of all the solar systems planets except Mercury.
- Hundreds of free-floating planets.
- Characterize the majority of host systems.
- Galactic distribution of planets.
- Sensitive to lunar-mass satellites.




(Penny et al. in prep)

# WFIRST+C Exoplanet Science

The combination of microlensing and direct imaging will dramatically expand our knowledge of other solar systems and will provide a first glimpse at the planetary families of our nearest neighbor stars.

## Microlensing Survey

Monitor 200 million Galactic bulge stars every 15 minutes for 1.2 years

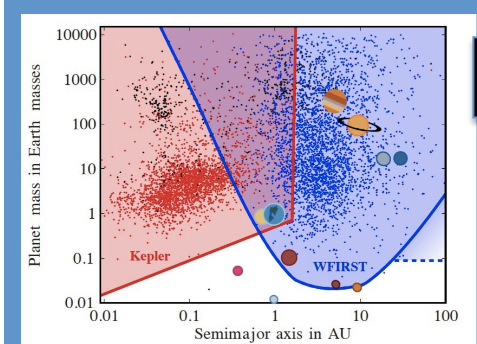
2800 cold exoplanets
300 Earth-mass planets
40 Mars-mass or smaller planets
40 free-floating Earth-mass planets

## High Contrast Imaging

Survey up to 200 nearby stars for planets and debris disks at contrast levels of $10^{-9}$ on angular scales > 0.2”
R=70 spectra and polarization between 400-900 nm

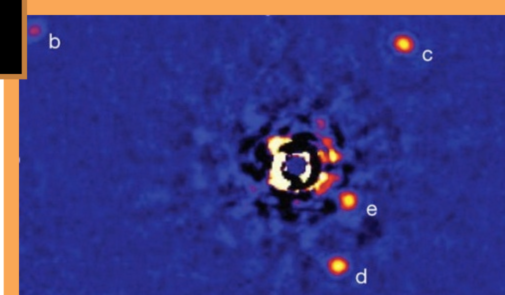
Detailed characterization of up to a dozen giant planets.
Discovery and characterization of several Neptunes
Detection of massive debris disks.

### Complete the Exoplanet Census




- How do planetary systems form and evolve?
- What are the constituents and dominant physical processes in planetary atmospheres?
- What kinds of unexpected systems inhabit the outer regions of planetary systems?
- What are the masses, compositions, and structure of nearby circumstellar disks?
- Do small planets in the habitable zone have heavy hydrogen/helium atmospheres?

### Discover and Characterize Nearby Worlds



# Toward the "Pale Blue Dot"

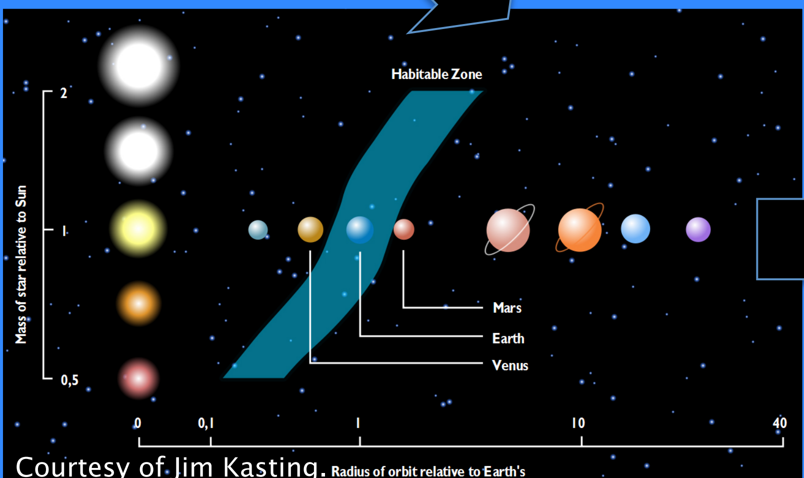
WFIRST will lay the foundation for a future flagship direct imaging mission capable of detection and characterization of Earthlike planets.

## Microlensing Survey

- Inventory the outer parts of planetary systems, potentially the source of the water for habitable planets.
- Quantify the frequency of solar systems like our own.
- Confirm and improve Kepler's estimate of the frequency of potentially habitable planets.
- When combined with Kepler, provide statistical constraints on the densities and heavy atmospheres of potentially habitable planets.

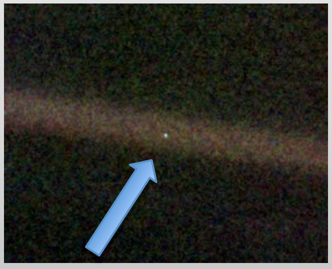
## High Contrast Imaging

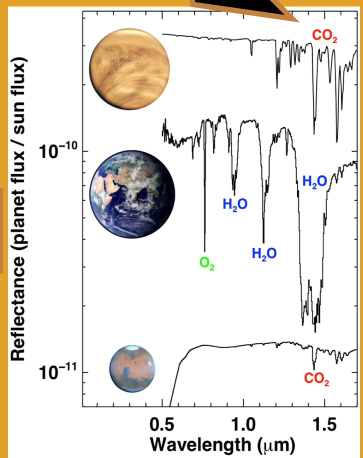
- Provide the first direct images of planets around our nearest neighbors similar to our own giant planets.
- Provide important insights about the physics of planetary atmospheres through comparative planetology.
- Assay the population of massive debris disks that will serve as sources of noise and confusion for a flagship mission.
- Develop crucial technologies for a future mission, and provide practical demonstration of these technologies *in flight.*




Courtesy of Jim Kasting.

Science and technology foundation for the New Worlds Mission.





# WFIRST µSIT.

- Scott Gaudi (OSU, PI)
- Dave Bennett (GSFC, Deputy PI, Pipeline/Algorithm Lead)
- Jay Anderson (STScI, Co-I)
- Sebastiano Calchi Novati (IPAC, Co-I)
- Sean Carey (IPAC, Co-I, Calibration Lead)
- Dan Foreman-Mackey (UW, Co-I)
- Andrew Gould (?, Co-I)
- Calen Henderson (JPL, Co-I, Precursor Data Lead)
- Matthew Penny (OSU, Co-I, Survey Optimization Lead)
- Radek Poleski (OSU, Co-I)
- Yossi Shvartzvald (JPL, Co-I)
- Rachel Street (LCOGT, Co-I)
- Jennifer Yee (CfA, Co-I, Outreach Lead)
- Chas Beichman (JPL, Collaborator)
- Geoffrey Bryden (JPL, Collaborator)
- Cheongho Han (Chungbuk National U., Collaborator)
- David Nataf (ANU, Collaborator)
- Keivan Stasssun (Vanderbilt, Collaborator)

Science Center Liasons
- Kailash Sahu (STScI)
- Sean Carey (IPAC)

Microlensing Preparatory Group Co-Chair
- Rachel Akeson (IPAC)

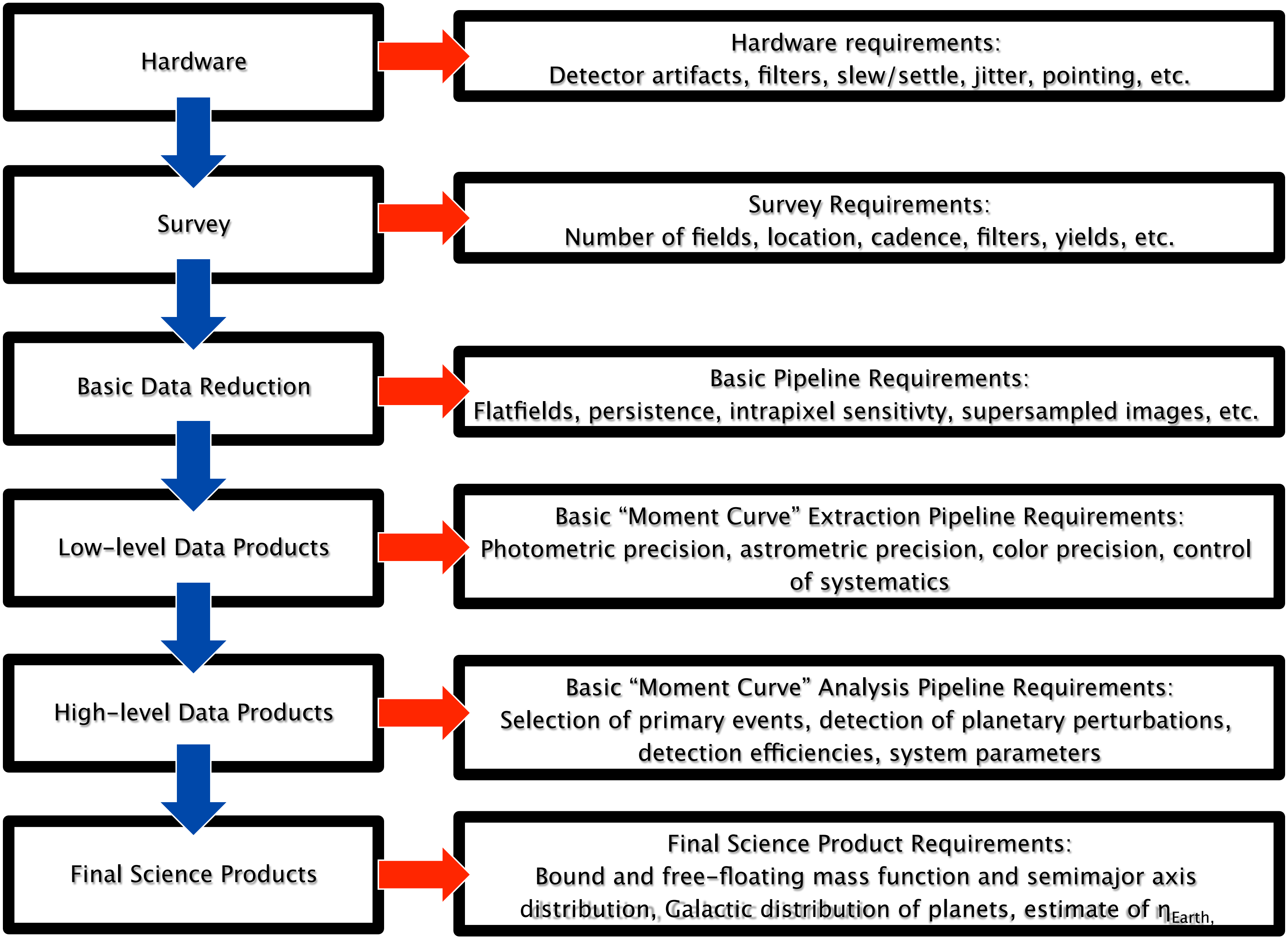
# Primary Goal.

*Develop a complete flowdown from the science goals of the microlensing survey to the mission design and hardware components.*

# Science requirements.

1. Measure the mass function of cold exoplanets with masses > 1 $M_{Earth}$ and semimajor axes ≥ 1 AU to better than ~ 10% per decade*.
2. Measure the frequency of Mars-mass embryos to ~ 15%*.
3. Measure the frequency of free floating planetary-mass objects in the Galaxy over nearly six orders of magnitude in mass. If there is one $M_{Earth}$ free-floating planet per star, measure this frequency to ~ 20%.
4. Estimate the mass and distance to the host stars and planets to better than ~ 20% for the majority of the detected systems.
5. Estimate $\eta_{Earth}$ via extrapolation from larger and longer-period planets.

*Assumes a fiducial mass function.


Hardware
Survey
Basic Data Reduction
Low-level Data Products
High-level Data Products
Final Science Products
Hardware requirements:
Detector artifacts, filters, slew/settle, jitter, pointing, etc.
Survey Requirements:
Number of fields, location, cadence, filters, yields, etc.
Basic Pipeline Requirements:
Flatfields, persistence, intrapixel sensitivty, supersampled images, etc.
Basic “Moment Curve” Extraction Pipeline Requirements:
Photometric precision, astrometric precision, color precision, control of systematics
Basic “Moment Curve” Analysis Pipeline Requirements:
Selection of primary events, detection of planetary perturbations, detection efficiencies, system parameters
Final Science Product Requirements:
Bound and free-floating mass function and semimajor axis distribution, Galactic distribution of planets, estimate of $\eta_{Earth}$,

# First Year Plan and Deliverables.

(1) Develop a detailed overall investigation plan for the full 5 years, define preliminary science goals and requirements flowdown.

(2) Initial assessment of the WFI requirements for the microlensing survey.

(3) Begin community outreach: software development and data challenges.

(4) Start development of data reduction algorithms.

(5) Identify needed auxiliary data.

(6) Begin trade studies and survey optimization.

# A Few Words About the WFI Pipeline and Calibration.

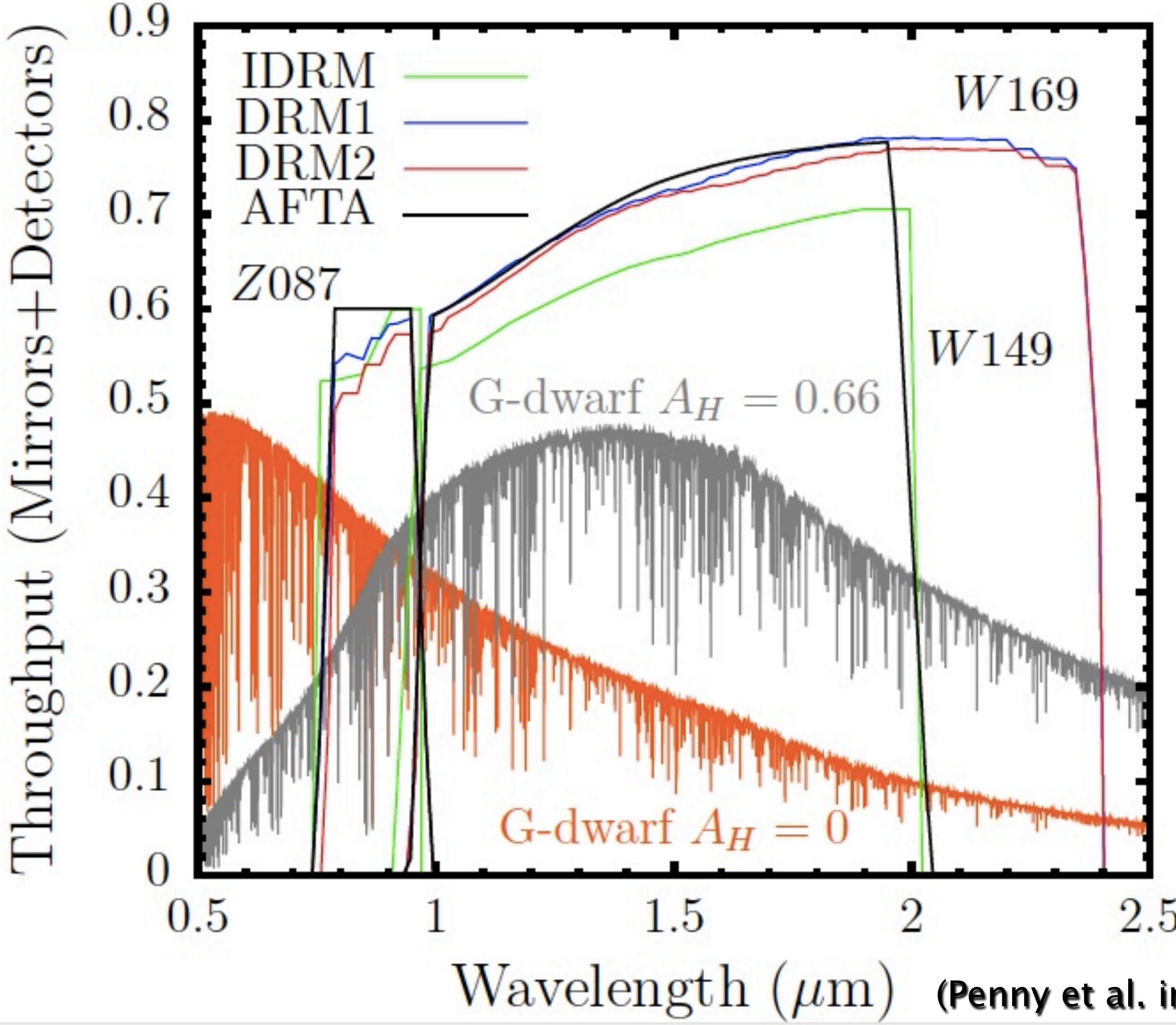
- The microlensing survey will likely provide the richest dataset for calibration of the WFI.
  - Few x $10^4$ observations of ~60 million point sources with $H_{AB}<21.6$ over ~5 years
  - Single-measurement photon-noise limited precisions of 1.2% and 1.7mas.
  - Will collect 2.5 billion photons for $H_{AB}=19.6$ star
- Yet the weak lensing survey will likely place the most stringent requirements on the WFI.
- Requires a holistic approach to calibration and pipeline, as well as the microlensing survey strategy.

# A Few More Words About the WFI Pipeline and Calibration.

- Development of the pipeline likely requires several different approaches:
  - Realistic simulated sky scenes.
  - Analysis of actual data that approximates the actual WFIRST data as closely as possible.
  - Intensive tests of actual detectors to provide quantitative and ground-truth estimates of the detector systematics.

# Summary.

- The primary goal of the WFIRST Microlensing surveys is to: ***"Complete the statistical census of planetary systems in the Galaxy."***
- A complete census is likely needed to understand planet formation and evolution, as well as habitability.
- WFIRST will complete the census begun by *Kepler*, and will revolutionize our understanding of cold planets.
- Will enable qualitatively new, exciting science by detecting thousands of planets over a broad range of parameter space, including analogs to all the solar system planets except Mercury.
  - Sub-Earth-mass planets, free-floating planets, outer habitable zone planets, mass measurements.
- Microlensing SIT will develop the complete requirements flowdown, from the hardware to the primary science goals.




(Penny et al. in prep)

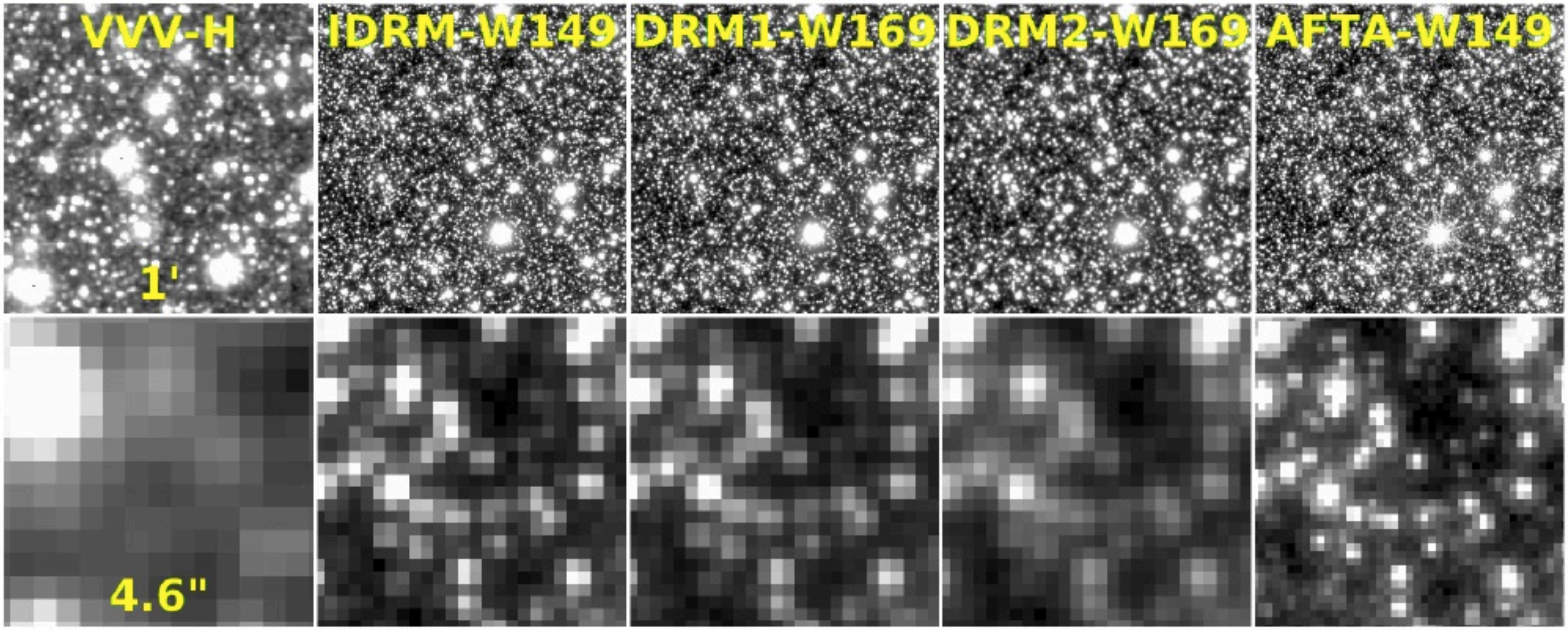
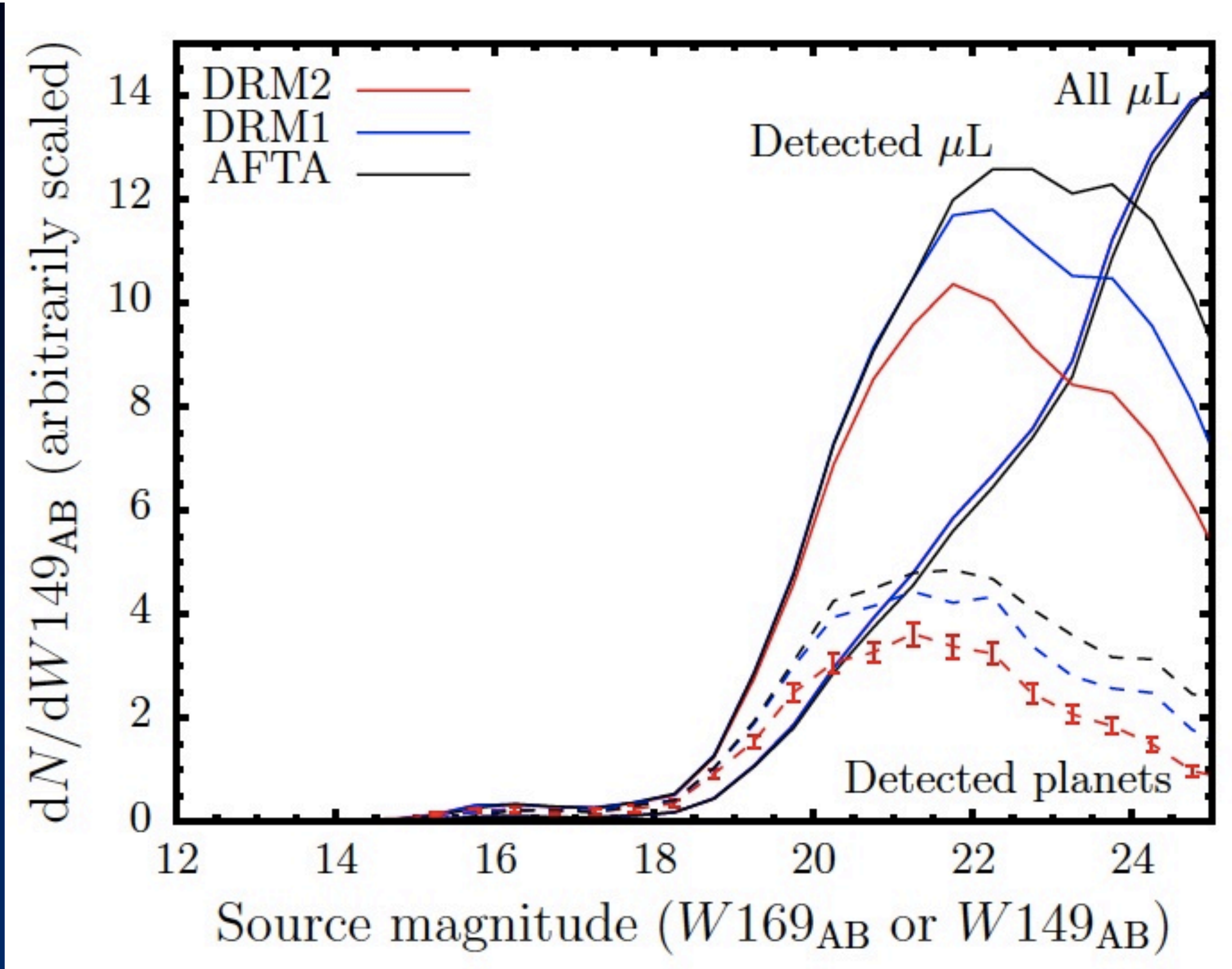



**Figure 2.** *Left column:* Section of a VVV $H$ band image (Saito et al. 2012) from near $(\ell, b) = (1.^\circ 1, -1.^\circ 2)$, which lies close to the center of the assumed WFIRST fields. *Right four columns:* Simulated images in the primary wide band of each WFIRST design of the same mock starfield drawn from the Besançon model sightline at $(\ell, b) = (1.^\circ 1, -1.^\circ 2)$. The top panels show a $1\times1$ arcmin region and the bottom panels show a $4.6\times4.6$ arcsec ($\approx 13\times$) zoom-in. The pixel sizes are $0.''339$, $0.''18$, $0.''18$, $0.''18$ and $0.''11$ from left to right respectively. Note that the apparent dark, tenuous, serpentine feature on the left side of the simulated images is a result of random fluctuations in the stellar density, and is not due to spatially varying extinction (e.g., a dust lane). VVV image based on data products from observations made with ESO Telescopes at the La Silla or Paranal Observatories under ESO programme ID 179.B-2002.

(Penny et al. in prep)

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